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EFFECT OF WETTING MODE ON SHEAR STRENGTH OF TWO AGGREGATED SOILS^{1/}

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ABSTRACT

High degrees of soil aggregation caused anomalously large angles of internal friction of 40°-42° for two cohesionless soils of the Oregon Coast Ranges. Soil aggregation and wetting by immersion during shear tests caused angles of internal friction of saturated soil to be atypically 9.5°-11° smaller than angles of internal friction of dry soil. Also, amounts of water-stable aggregates were 23 to 35 percent less after saturation by immersion of soil samples than after saturation by tension wetting. This suggests that the mode of wetting a sample may influence the apparent angle of internal friction for such soils.

KEYWORDS: Soil testing, soil stability.

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INTRODUCTION

In soil stability problems, knowledge of soil shear strength parameters is required. Determination of the proper values of the strength parameters to use in a stability analysis can be the most difficult task in soil engineering. In tests for shear characteristics, external forces are applied to the soil test specimen in such a way as to cause adjoining parts of the specimen to slide (shear) relative to each other. The stress developed within the soil, in opposition to shearing, is termed shear resistance. The shear resistance developed at failure is the shear strength of the soil. The ratio of shear strength to shear stress along a critical sliding surface within a soil mass is the factor of safety (F) of the soil mass. The soil mass will fail or is about to fail if F is ≤ 1.0 .

Soil shear strength is generally considered to be a function of apparent cohesion, intergranular friction, and effective normal stress. This relationship, called Coulomb's Law, is given by:

$$S = c' + \sigma' \tan \phi' \quad ;$$

where,

- S = shear strength
- c' = cohesive strength
- σ' = effective stress normal
to the shear surface
- ϕ' = angle of internal friction.

Shear parameters are not physical constants; they vary with stress history, soil structure, degree of disturbance, degree of packing and density, and water content of the soil. For example, clay soils are normally strong when dry but may be very weak when wet. Therefore, in soil strength tests, the condition of the test specimen must represent as nearly as possible the appropriate field condition of the soil at the time of critical stability.

The test method may also affect shear strength values. If drainage from a saturated soil specimen during a shear test is prevented, pressure develops in porewater, and strength is reduced. This reduction occurs because shear strength is proportional to the effective pressure between the soil particles, which, in turn, equals total pressure minus porewater pressure. Thus, for constant total pressure, increased porewater pressure decreases strength (Terzaghi and Peck 1967).

Shear strength tests have not been completely standardized because considerable freedom in testing procedures is necessary for properly testing soil samples to determine their behavior under field stress conditions. All shear strength test methods, however, do recognize the importance of adequately defining the drainage and consolidation conditions during the test.

The purpose of this study was to determine if the stability of soil aggregates and the method of saturating a test sample could influence the strength parameter values for two cohesionless soils--soils which rely almost entirely on intergranular friction for strength and are usually granular and nonplastic.

SOIL TESTING

Sample of Klickitat and Bohannon soils from four sites in the central Coast Ranges of Oregon were tested. Klickitat soils are derived from intrusive igneous rocks; the Bohannon soils are derived from arkosic sandstone. Together, these two soils occupy over 90 percent of the area having cohesionless soils in the central Coast Ranges (Corliss 1973). Both are commonly found on the steepest and most sensitive slopes.

Soils were tested in the laboratory to determine their strength characteristics and the stability of their aggregates. Because Atterberg Limits tests and preliminary triaxial shear testing indicated soils were cohesionless, we used the triaxial test procedure described by Lambe (1951, p. 98-109) to determine angles of internal friction (ϕ') of air-dried samples. Since suitably undisturbed soil samples could not be obtained because of the friable, cohesionless nature of the soils, samples were reconstructed to approximate field densities. No roots or other large pieces of organic matter were included in the reconstructed soils. We used a modification of Kemper's (1965) procedure to determine aggregate stabilities of soils wetted under tension and by direct immersion. Further details of laboratory tests are given in Yee (1975).

RESULTS AND DISCUSSION

Shear Tests

Results of shear tests are summarized in table 1. Values of angles of internal friction (ϕ') for dry soil averaged about 41° , much higher than expected for such loose, porous soils. For example, dry, loose sands and silty sands tested under effective stresses (σ') of 5 kg/cm^2 ^{3/} commonly exhibit values of 27° - 33° (Terzaghi and Peck 1967). We could find no comparable cases in the literature where such loose, highly aggregated soils were tested.

^{3/} Here we follow the common engineering practice of expressing mechanical stress in units of force per unit area. Mechanical stress is correctly expressed in units of mass per distance x time squared (M/LT^2) or in newtons per square meter. One kg/cm^2 equals 9.807×10^4 newtons/ m^2 which equals 1 pascal, the standard international unit of stress.

Table 1--Results of triaxial shear testing of dry and saturated Klickitat and Bohannon soils^{1/}

Soil series	Soil condition	Initial porosity	Angle of internal friction (ϕ')	Decrease	"t" statistic	Strain at failure	"t" statistic
		Percent		Percent		Percent	
Klickitat	Dry	61.4	41.49°			5.7	
	Saturated	61.3	32.00°	23	10.85*	11.0	10.82*
Bohannon	Dry	60.6	40.46°			5.2	
	Saturated	60.0	29.31°	28	14.63*	10.8	8.01*

*Statistically significant at the 0.1-percent level of probability.

^{1/} Values for porosity, internal friction (ϕ), and strain are means of five samples.

The anomalously large angles of internal friction are attributed to the high degree of aggregation found in these soils. Because the stability of the aggregates of both soils was sufficient to resist substantial dispersion techniques during particle-size analyses (Lambe 1951, p. 29-42), particles in the soil framework were assumed to be stable enough to function as individual primary particles, at least for the range of effective stresses under which testing took place. These large, composite particles tend to increase the grain interlocking and make the framework more resistant to stress. Large, composite particles functioning as primary units tend to have greater angularity, rougher surfaces, and larger effective sizes than would individual particles. This is especially true for more weathered soils which have more rounded and platelike individual particles. Therefore, the high degree of aggregation, coupled with the high aggregate stability, apparently produced the unusually high ϕ' values in these soils. Shear of these soils may involve considerable breaking of the grains as well as rolling and sliding.

From Coulomb's equation, it is apparent that the higher ϕ' values for both soils should produce greater shear strength for the same effective stress. For soils on steep slopes, high ϕ' values have important benefits for maintaining slope stability.

The large differences in ϕ' values, 9.5°-11° less in saturated soils than in dry soils, are also anomalous (table 1). Reductions of this magnitude are atypical compared with those of other studies of the effect of water on the angle of internal friction of cohesionless soils. According to Terzaghi and Peck (1967) and others, there should not be a reduction in ϕ' because of moisture in a cohesionless soil. Also, no significant change in the strain at failure should occur. In this study, the large differences in angles of internal friction between dry and saturated soils are attributed to the high degree of aggregation and the stability of aggregates.

A major factor affecting the stability of wetted aggregates is the mode by which they are wetted. One mode, direct immersion of a dry soil in water at atmospheric pressure, causes the greatest disruption of aggregates (Kemper and Chepil 1965). Air is trapped within the aggregate by such rapid wetting, and the air is compressed by the advancing water film. This air bursts the aggregate's structure when it is sufficiently weakened by hydrating (Emerson and Grundy 1954). These miniature explosions can disintegrate aggregates.

The other possible mode of water entry is wetting under tension, the normal mode of wetting for subsurface soils (Kemper and Chepil 1965). The slower wetting under tension results in very little entrapment of air and hence less disruption of the aggregates in the main body of soil (Kemper 1965).

The influence of the wetting mode on soil aggregates is shown in table 2. The effect of direct wetting was extremely detrimental to the aggregates, and severe reductions in aggregate content occurred in both soils. Paired "t" tests (Snedecor and Cochran 1956) showed reductions are statistically significant at the 0.1-percent level of probability.

Table 2--Aggregate stability of Klickitat and Bohannon soils saturated under tension and by direct immersion

Soil series	Soil pit	Stable Aggregates		Decrease	Number of sample pairs	"t" statistic
		After tension wetting	After direct immersion			
----- <u>Percent</u> -----						
Klickitat	A	84.2	62.7	26	6	8.73*
	B	83.8	64.3	23	8	10.47*
	A + B	84.0	63.6	24	--	--
Bohannon	C	88.6	63.1	29	14	11.96*
	D	86.3	56.1	35	6	7.27*
	C + D	87.9	61.0	31	--	--

*Statistically significant at the 0.1-percent level of probability.

The influence of the wetting mode on aggregates of both soils possibly explains the results of the shear tests. During the saturated shear tests, samples were saturated under only a slight vacuum in order to avoid sample consolidation, a potential problem with the low sample densities used. Consequently, the samples were saturated by direct wetting, and many soil aggregates were destroyed; others were weakened. Composite particles which had previously acted as single, primary units with larger effective sizes, greater angularity, and increased surface roughness, were reduced to smaller, more platelike and rounded particles. This most likely decreased the intergranular friction angle of both soils.

Shearing resistance caused by interlocking of grains was most likely also reduced. Such interlocking accounts for a substantial portion of the total shearing resistance of loose, cohesionless soils (Chen 1948) and requires that some grains be lifted and rolled over others as sliding occurs along the failure planes. Since the motion of individual particles--in this case, composite aggregated particles--has a component normal to the plane of failure, a considerable amount of work required to produce failure must be used in overcoming the resistance which the normal force offers to this motion. If a substantial number of primary particles are reduced to their smaller individual components, the amount of interlocking resistance would probably be reduced because adjacent grains would have a smaller distance to be lifted. The same is true for aggregates not completely destroyed but merely weakened. Weakening of intra-aggregate bonds would allow failure to occur within as well as between aggregates. Again, the amount of work necessary to overcome interlocking would be reduced. Composite particles whose bonds were merely weakened also experienced greater distortions before sliding commenced and produced the greater failure strains observed during testing of saturated soils (table 1).

The 23-percent decrease in the average angle of internal friction for the Klickitat soil and 28-percent decrease for the Bohannon soil (table 1) were accompanied by 24- and 31-percent decreases, respectively, in the average aggregate stability (table 2). Whether or not samples saturated under conditions of tension wetting and subjected to shear would yield ϕ' values closer to those under dry conditions is unknown. If we consider the greater percentage of aggregates remaining intact under tension wetting for both soils, the ϕ' value for a sample wetted under tension might be closer to the ϕ' value of a dry sample than to the ϕ' value of a sample wetted by immersion.

Application of Results

Because mode of wetting may greatly alter soil strength, the engineer conducting shear tests must monitor the drainage during shear and the wetting mode used in saturating soil samples. If he believes the angle of internal friction for cohesionless soils is not greatly affected by water, then he may test such a soil in the dry state because such testing is simpler and faster. If the soil is aggregated, however, he would obtain a higher ϕ' value than he would if he tested a soil in a saturated state. In either case, the ϕ' value could be erroneous and nonrepresentative of what would occur under field conditions of wetting.

Using the ϕ' value for a dry soil may be adequate for analyzing dry soils and tension-wetted soils but might be hazardous for analyzing such soils on a slope that could be subjected to direct wetting. For example, consider a situation which could arise when water from a newly constructed ditch-culvert drainage system empties onto soil below a forest road. A system of ditches and cross-draining culverts is the most common means of controlling runoff from forest roads in the Pacific Northwest, and culverts empty into

linear depressions, onto sidehill slopes, or into established watercourses. Some shallow soil is usually present in most linear depressions on steep slopes. The soil in the depression may have carried saturated subsurface flow, but this saturation occurred under tension. Now, with the road present, the new culvert periodically may deposit varying quantities of water into the depression and subject the soil profile below the culvert to direct wetting. The flow of water may not be enough to wash away the soil nor to cause an increase in porewater pressure sufficient to initiate sliding, but some soil aggregates may be destroyed or weakened.

Lowering the angle of internal friction in this portion of the soil could create a small weak point along the potential failure plane. The soil, however, may not fail at this time. Although some of the deaggregated soil particles may even reaggregate over time (Lutz and Chandler 1961), usually neither the total number of aggregates nor the overall degree of aggregation is as great as it was initially. As subsequent inundations occur, the zone of aggregate destruction may increase or spread and intensify in areas previously deaggregated. At some future date, perhaps after many years, the factor of safety (F) is reduced to the point where failure occurs. Figure 1 illustrates the process described. Areas 1, 2, and 3 reflect the hypothesized portions of the soil profile affected by inundation events and, hence, have had their angle of internal friction (ϕ') lowered. At some event n , the reduction in F to or below 1.0 causes the slope to fail. This may explain in part why some road-associated slope failures occur during moderate rainfall rather than heavy rainfall.

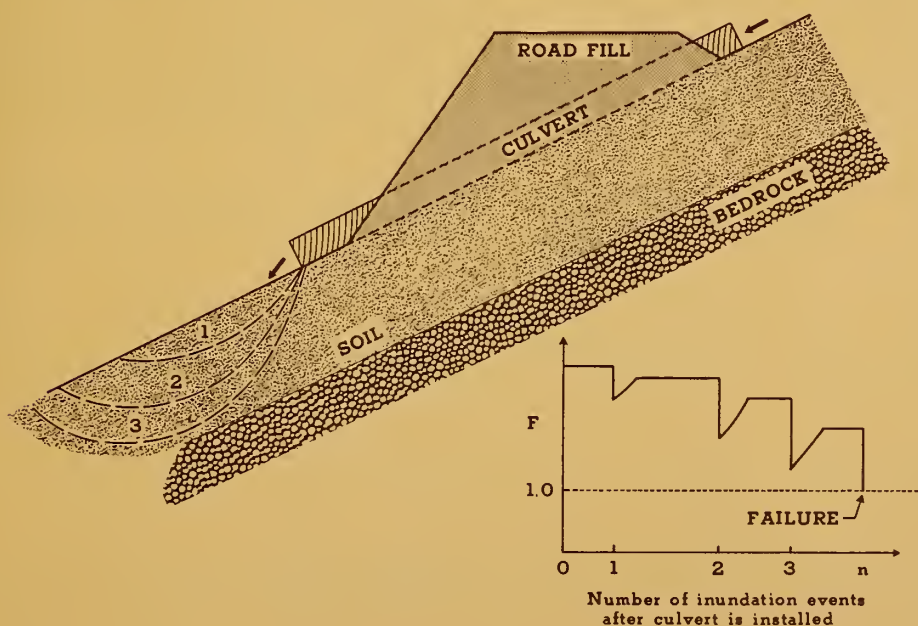


Figure 1--Potential progressive weakening of a soil mass after inundation of soil by culvert outflow.

SUMMARY

Soil aggregation and mode of wetting during shear tests of two apparently cohesionless soils caused angles of internal friction of saturated soil to be 9.5° - 11° smaller than angles of internal friction of dry soil. Amount of water-stable aggregates was 23 to 35 percent less after saturation of soil samples by immersion than after saturation of samples under tension. Because mode of wetting of some apparently cohesionless soils may affect their strength parameters, the field conditions of wetting soils must be considered when strength test procedures are planned.

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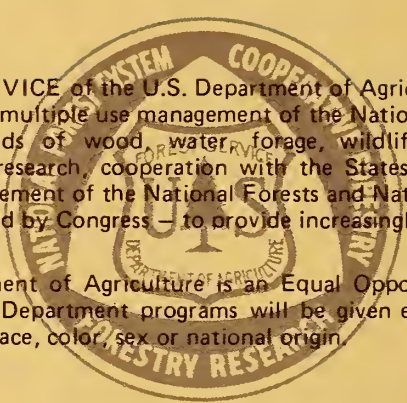
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